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Secretary, Federal Communications Commission
1919 M St. NW
Washington DC 20554

MM Docket No. 87-286

Dear Sir:

Enclosed is the original and six copies of my comments in response to the Fifth Further Notice of Proposed Rule Making in the cited docket. I reserve the right to submit further comments before the deadline of 11 July 1996. I have also sent copies directly to the Commissioners.

Very truly yours,

W. F. Schreiber

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Before the Federal Communications Commission
Washington DC 20554

In the Matter of
Advanced Television Systems
and Their Impact upon the
Existing Television Broadcast Service

MM Docket 87-268
Fifth Further Notice of Proposed Rule Making
Submitted 14 June 1996

Comments of

William F. Schreiber
Senior Lecturer, Professor of Electrical Engineering, Emeritus
Research Laboratory of Electronics
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The opinions in these comments are those of the author only.
He has no financial dealings with any computer company.
Since his retirement in 1990, the author has had no role in
directing MIT's Advanced Television Research Program.

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Executive Summary

The imminence of a new set of television broadcasting standards presents a rare opportunity to make a quantum advance in spectrum efficiency, image quality, and interoperability. Actually achieving this highly desirable set of potential improvements requires the exclusive use of progressive-scan (P) formats for transmission. Not only are interlaced formats (I) deficient in these characteristics, their use will inhibit any migration to progressive scan, which is agreed by all parties to be the final objective. The use of interlaced transmission will effectively eliminate the possibility for the system to be improved over time in a manner that does not make unusable much of the first-deployed equipment, especially receivers in the hands of the public.

The scientific evidence for this view has been available for some time, as detailed in my Informal Reply Comments to the Fourth NPRM, submitted to the Commission on 8 March 1996. In that submission, I showed that *no advantage, economic or otherwise, is gained from the use of interlace by any stakeholder in the television industry.* There did remain the problem that no satisfactory HDTV camera had yet been developed for progressive scan. However, the Polaroid Corporation has now introduced a very high-quality HDTV camera that uses the 720x1280x60 fps Grand Alliance progressive standard. Based on the ATTC/ATEL test results, it is the author's opinion that the progressive-scan systems would have won the competition had the Polaroid camera been available for the testing. This development has disposed of the last possible argument for including as archaic a technique as interlace in the coming standards. *The Commission is urged to include only progressive formats in the new standards for both HDTV (high definition) and SDTV (standard definition).* To avoid the development of a serious reverse-compatibility problem that would prevent further improvements of the system over time, *the Commission is also urged either to require that all over-the-air transmissions be of the highest possible resolution permitted by the standards, or to require interlaced receivers to incorporate vertical low-pass filters.*

Introduction

Interlace was originally used to raise the large-area flicker rate for a given number of lines per second and lines per frame over what it would have been with progressive scan. The process can as well be thought of as attempting to double the vertical resolution at a given large-area flicker rate with a given number of lines per second. In this attempt, it mostly fails except at very low brightness. At normal brightness, the resolution improvement is only about 10% (See the 1967 Brown paper in the Appendix.) while, at the same time, serious artifacts are introduced -- interline flicker in detailed image areas and aliasing effects around vertically moving sharp edges

When interlace was first introduced, its artifacts were not very noticeable because of the generally low resolution of TV equipment and because existing quality standards were not very high. Even today, most TV cameras, both tube-type and CCD-type, have such low vertical resolution (about half the number of lines per frame) that interline flicker is hardly noticeable. This is particularly true of interlaced HDTV cameras, whose resolution, relative to 1125 lines, appears to be substantially lower than the resolution of good NTSC cameras, relative to 525 lines.

Where the video data has full vertical resolution, such as in applications in the computer industry and in air-traffic control, interlace has been abandoned. Close viewing of fine detail on interlaced displays is intolerable after a short time. Interlace also complicates transcoding, so that, even after 30 years' effort, NTSC-PAL conversion is still far from perfect. For such reasons, virtually everyone concerned agrees that interlaced scan is inferior and that the US digital standard should eventually migrate to progressive scan. The main reason usually given for using interlace at first are:

1. Interlace doubles the vertical resolution for a given bandwidth and frame rate.

2. Progressive scan, in analog or coded digital form, requires more bandwidth or channel capacity than interlace for the same resolution -- another way to put the same idea.

3. Interlaced equipment, particularly receivers, are cheaper.

4. No one knows how to make progressive scan HDTV cameras with adequate sensitivity.

5. Many programs that will be used with standard-definition (SDTV) transmission exist in interlaced form.

As we shall see in what follows, all of these arguments are incorrect. *There are no valid reasons for using interlace in DTV, and there are many good reasons for using progressive transmission only.*

The ATTC/ATEL Test Results

Tapes of the output of the five proposed systems for each of 9 still images and 15 sequences, made by ATTC, were used in subjective testing of overall perceived quality conducted by the Advanced Television Evaluation Laboratory (ATEL) in the Canadian Dept. of Communication. Fig. 1 shows the final result of the first stage of the subjective-testing program, held in 1991-92. For all but two of the test images (S14 and M16), an 1125-line, 30-f/s interlaced camera was used, the input video for the two progressive-scan systems being derived from the interlaced video in a scan converter. One still image and one image sequence were computer-generated. The rating was in terms of subjective units relative to the uncoded 1125-line originals. S14 and M16 were computer-generated.

It is evident from these results that all systems suffered some loss in quality relative to the 1125-line interlaced input. The apparent superiority of the progressive systems for the computer-generated motion sequence was later accounted for by an error in generation of the interlaced sequence: the odd and even fields were interchanged, depressing the quality of the reference signal as well as the outputs of the interlaced systems.

Fig. 2 shows the results of the second test, held in 1994-95, in which only the Grand Alliance 720P and 1080I formats were tested. The computer-generated scenes, now called S14A and M16A, were redone. In the second test, the overall quality was higher and there was no systematic difference between the two formats. The dynamic vertical resolution of the P system was slightly higher than that of the I system, in spite of having only 720 scan lines as compared with 1080 scan lines. (The horizontal resolution was somewhat less, as expected.)

One point that seems to have been lost in the testing process was that the progressive material scan-converted from the interlaced video in all likelihood had much less than 720 lines vertical resolution, so that a portion of the capabilities of the progressive coding system actually went to waste. I have never seen even the slightest interline flicker on an 1125-line display, whereas some such flicker is usually present in the output of a high-quality NTSC camera. The actual vertical resolution of the 1125-line cameras is probably less than 600 lines. It is my opinion that, if the Polaroid camera had been available at the time of testing, the progressive format would have had higher overall quality on account of superior vertical resolution and may well have won the competition. If special scenes had been included that showed interlace artifacts, I think there is little doubt that this would have been the case. In any event, the 1080 interlaced format, in spite of having more than twice as many picture elements per frame, did not have higher perceived overall quality

Technical Background

In a system in which camera, transmission channel, and display all have the same interlaced scan format, interline flicker (at 30 Hz in NTSC) will be seen in all areas of the image where detail can be seen. This is because adjacent scan lines (necessarily in successive fields) are not identical. Note that the scan lines do not have to be resolved either by the eye or by the CRT for this flicker to be seen. As long as the horizontal extent of the detail on adjacent lines

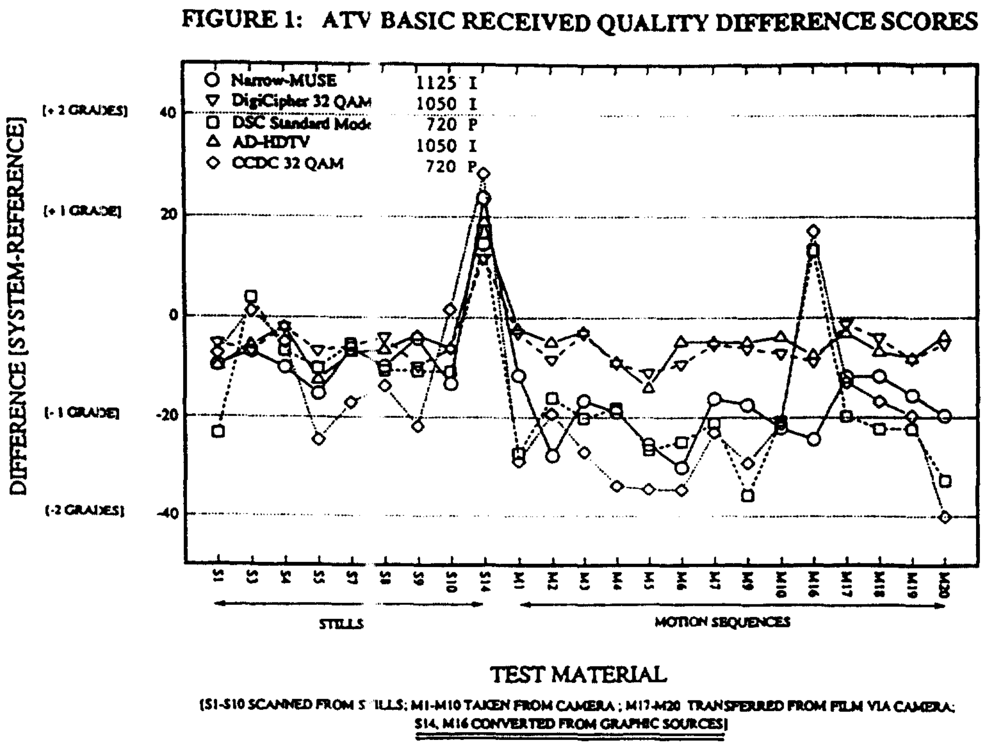

Figure 1. Perceived Overall Quality in the First-Round Test

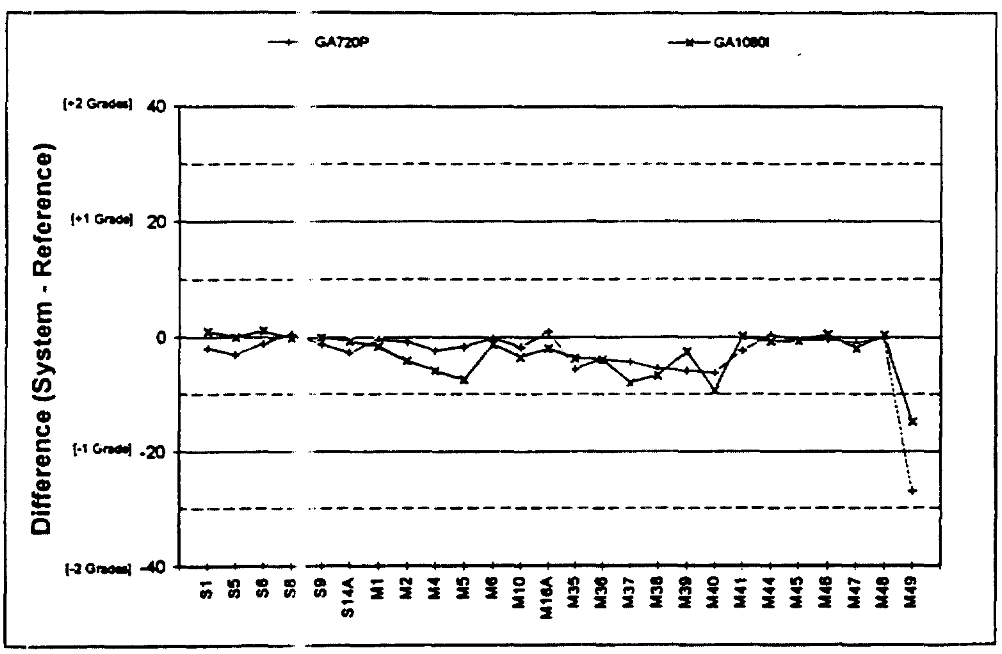

Figure 3.2 Quality of the Digital HDTV Grand Alliance system across all sequences compared with the 1125-line studio quality reference.

Figure 2. Perceived Overall Quality in the Second-Round Test

is visible and different, interline flicker occurs at the frame rate. For example, a picture with alternate white and black lines -- unusual, but a legitimate NTSC image -- would flicker at 30 Hz even when viewed from across the room.

This phenomenon is not very troublesome in today's system because interlaced cameras, using either tubes or CCDs, integrate over one field time, and not one frame time, thus reducing the vertical resolution by half and making adjacent lines more similar. This "defect" is essential to make the display at all acceptable. Shifting to integration over a frame time rather than a field time would restore the vertical resolution, but would introduce other serious defects, such as serrated vertical edges on horizontally moving objects. Upconversion to a progressive display at the receiver can remove some problems, but is very expensive. The argument for interlace, if there is one, is to make the receivers cheaper, not more expensive.

If there is no interline flicker on an interlaced display, the system is behaving much more like a system with progressive scan with double the frame rate and with half the number of lines per frame. (This point is made in the ACATS Final Report.) This is the case in most sports use, which is why motion rendition in NTSC is so much better than in 24-fps film. The TV frame rate is, in effect, 60 fps rather than 30 fps, and the frame-rate ratio compared to film is 2.5:1 rather than 1.25:1. Up-conversion at the receiver in this case is pointless.

Another problem is that interlace greatly complicates transcoding. All TV signals have a great deal of temporal aliasing because the frame rate is not high enough relative to the amount of motion. Even for quite ordinary fast action, hundreds of frames/sec would be needed to get alias-free imagery. In the presence of temporal aliasing, interlace makes transcoding very difficult because the successive fields are displaced in both space and time.

The Polaroid Camera

Polaroid has for some time been a developer and manufacturer of CCD chips for consumer cameras. ARPA has for some time been concerned with meeting military requirements for high-resolution nonflickering imagery from domestic sources. This is the background for the project to develop a progressive-scan chip and complete camera for HDTV, which was sponsored in part by ARPA. (ARPA is sponsoring two other projects of a similar nature.)

Since Polaroid is not a manufacturer of commercial TV cameras, they cooperated with BTS (Broadcast Television Systems, owned in large part by Philips) in a program to use the new 720x1280 progressive chip in the existing LDK 9000 camera, which normally operates in the European 1250-line, 50-fps interlaced format. While extensive changes were required to use the new chip, these were, for the most part, straightforward engineering developments.

The development and specifications of the camera are described in a paper in the Appendix. For the purposes of our argument, it suffices to say that the camera has high resolution together with sensitivity not less than that of the LDK 9000 operating in the interlaced mode. The new camera is fully adequate for the most demanding HDTV applications. Its output, naturally, is free of all interlace artifacts. Since it is based on an existing fully engineered camera with a successful record of application, it is ready for everyday use when HDTV broadcasting starts.

Operational Considerations

In NTSC, no transcoding is required since the programs are produced, broadcast, received, and displayed all in the same format. In DTV, each program will be MPEG-coded and transmitted as a digital data stream modulated onto a carrier. In the receiver, the decoding and reconstruction requires frame memories. By writing into a frame memory in one standard and reading in another, transcoding can be accomplished, so that the display format is not necessarily the same as the production and transmission format. Normally, however, the scan format of the reconstructed signal will be the same as that of the signal into the encoder.

When transmitting a multiplicity of standard-definition programs in one channel, a scheme now used in satellite broadcasting and very likely to be used in cable, coding can be done either before or after multiplexing into one signal for transmission. If progressive transmission is mandated, then any existing interlaced material, such as archival NTSC, must be upconverted to progressive scan before coding. The cost of the needed I-to-P converter is much higher than the P-to-I converter used in the receiver, but would be entirely negligible compared to the cost of installing the equipment needed for digital transmission. In some cases, conversion to progressive scan would be helpful to the compression process *In no case does interlace increase the compressibility of standard-definition video.* (See my letter of 8 June to Mr. Hundt in the Appendix.)

There is no substantial archive of HDTV video material in interlaced format. Film libraries would supply a considerable portion of the HDTV broadcasts. The film would be scanned in progressive format at a cost no higher than scanning in interlaced format. Live shows would use a progressive camera such as Polaroid's, so no conversion would have to be done.

Interlaced receivers would have to have P-to-I converters if progressive transmission were used. This is a simple process in which half the lines are discarded, the remaining lines being doubled in duration. The incremental cost of these converters would be very small, because the MPEG decoder must have one or more frame memories. These memories could readily be used for a simple converter, with almost no increase in cost of the receiver. These receivers would also need vertical low-pass filters to prevent interline flicker. Again, the additional cost of such filters would be very small considering the powerful processing engine that the decoder requires. *The conclusion is that there is no significant economic penalty to anyone from the exclusive use of progressive transmission in DTV. If this is the case, and if the system is to migrate to progressive scan at a later date, as agreed by all parties, then the use of interlace, even at the beginning of broadcasting, has no justification whatsoever.*

If only progressive transmissions with full vertical resolution are permitted, then the difference in performance between interlaced and progressive receivers will be quite evident at the point of sale, and we can safely rely on the market to make its judgment. On the other hand, if interlaced transmission is permitted, then interlaced receivers that are perfectly adequate for displaying early interlaced DTV program material -- either HDTV or multiplexed NTSC -- will flicker unacceptably at a later time when displaying material converted in the receiver from full-definition DTV broadcasts. (Receivers that lack

P-to-I converters will be entirely unusable with such broadcasts.) Since the defects will not be apparent when the receivers are purchased, the market cannot be relied upon to ensure that the public will be protected. One way to deal with this is to require that appropriate technology be used in the receivers (just as all receivers are required to operate with UHF broadcasts), or , at the very least, to require labelling that indicates the problem. Alternatively, broadcasting parameters can be mandated so that the market will ensure that appropriate receiver technology is used.

A point that should be mentioned is that nearly 3 million set-top boxes are now in use for receiving digital satellite broadcasts. These broadcasts, at present, are all comprised of multiple NTSC signals that have been multiplexed and coded. Most of the boxes (such as Digicipher 2) are MPEG-compliant, but none can handle 1080 interlaced broadcasts, not to mention the 1080 progressive format to which the terrestrial system is supposed to migrate. These boxes would also not be capable of dealing with standard-definition progressive broadcasts. This situation has arisen because of the Commission's decision to permit the technical standards for satellite transmission to be unregulated except for interference issues.

An argument can be made that the Commission should allow interlace for standard-definition signals so these boxes can be used. I suggest that taking these boxes into consideration in setting the DTV broadcast standard would be a mistake. It would be tantamount, not only to giving up progressive scan, which I believe to be superior, but to giving up HDTV, of which existing boxes are incapable. This is contrary to the Commission's earlier decision that improving the technical quality of TV reception was in the public interest.

Some lessons may be learned from history. At the time of the 1953 NTSC color decision, the existence of less than 10 million monochrome receivers was used as a reason to select a receiver-compatible color system. (We now have nearly 200 million receivers.) Not only did this greatly reduce the resolution and produce the well-known artifacts of composite color, it also greatly reduced the motivation to buy color receivers. NTSC color very nearly failed, as it took 10 years to reach the 1% penetration point. Note that the perceived difference between monochrome and color is much larger than the difference between analog and digital pictures or between standard definition and high definition. If we expect people to rush out and buy digital receivers, we must provide attractive programming that they cannot get with their existing sets, together with the highest possible technical quality. If we fail to do this, then it will become politically impossible to turn off NTSC and to achieve the very much higher spectrum efficiency that is promised by the new systems.

The Literature

The technical conclusions presented in these Comments are not secrets held by a few. They are conclusions of papers from reputable laboratories that have been available to workers in the field for some time. In the Appendix, we include the following references:

1. E.F.Brown, "Low-Resolution TV Subjective Comparison of Interlaced and Noninterlaced Pictures," Bell System Tech. J., 46, 1, 1967, pp 199-232.

In this early paper, Brown showed, by a very careful series of experiments, that the increase in vertical resolution obtained by changing from progressive scan to interlace, keeping the same line-scanning rate and bandwidth, depends on the luminance of the display, and is only about 10% (rather than 100%) at brightness and resolution typical of modern television practice.

2. E. Petajan, "A Video Compression Efficiency Analysis using Progressive and Interlaced Scanning," AT&T Bell Laboratories, presented at the NIST Conference, Georgetown University, 1994, and at NAB 1994.

For a variety of scenes, Petajan shows that the picture quality using progressive scanning is equal to or better than the picture quality using interlace, when coded to the same digital data rate. The analog progressive video has twice the bandwidth of the analog interlaced video, so the compression ratio for progressive is twice that for interlace, while the progressive output is entirely devoid of interlace artifacts.

3. S.Pigeon and P. Guillotel, "Advantages and Drawbacks of Interlaced and Progressive Scanning Formats," EU Report R2110/WP2/DS/R/004/b1 commenting on the Scanning Formats Recommendation for Project Race in Jan. 1994.

The authors conclude that, while it would be uneconomic to change PAL to a progressive format, on the occasion of moving to digital transmission, only "minor costs compared to the overall budget" would be entailed by using progressive scan. It is also concluded that the "progressive format may be coded using the same bit rate as interlaced at same or improved picture quality." They also propose modifying the MPEG2 MP@ML format to permit using 50-Hz progressive scan.

4. M. Muratori (RAI), M. Stroppiana (RAI), and Y. Nishida (NHK), "Progressive and Interlaced Formats: Comparison and Coding Efficiency." (Similar to a paper by the same authors presented at the 1993 IEICE Spring Conference.)

The authors conclude that if typical interlaced and progressive sequences are vertically low-passed filtered to obtain the same static vertical resolution, the progressive sequence having twice the analog bandwidth of the interlaced sequence, that the same digital data rate may be used with either. They also claim 3 dB lower coding noise for the progressive pictures, but do not deal with the possibility that a progressive camera may be noisier than an interlaced camera. (This report was written before the announcement of the Polaroid camera.)

5. "Further Results on the Comparison of Coding Efficiency Between Progressive and Interlaced Formats," Doc. TG CMTT/2-SRG-088 submitted to the CCIR Study Group TG CMTT/2 Jan. 1993.

Confirms the results of an earlier report (SRG-068) to the effect that interlaced and progressive sequences of equal static vertical resolution can be coded to the same digital data rate.

The conclusion from these papers is that interlace does not improve the compressibility of video programs. Progressive transmission with its inherently higher quality, requires no higher coded bit rate.

6. S.M.Spitzer et al, "Design and Implementation of a 3-CCD, State of the Art. 750-line HDTV Progressive Scan Broadcast Camera." NAB 1996

This paper gives technical details of the design of the Polaroid progressive-scan camera.

7. Letter from the author to Mr. Hundt on 8 June 1996 relative to the effect of the I/P format on compressibility when a number of standard-definition programs are multiplexed into one 6-MHz channel.

8. Letter from the author to Mr. Hundt on 9 May 1996 relative to the significance of the Polaroid progressive-scan camera.

The FCC Decision

The Federal Communications Commission was originally established at the urgent request of the radio broadcasting industry to bring order out of chaos by establishing rules for radiating signals and issuing licenses in a fair and open manner. As technology advanced, a main aspect of the Commission's responsibilities, in addition to granting licenses to broadcasters and avoiding interference, became protecting the public interest in an environment of rapidly increasing spectrum use. At no time has anyone ever advanced the theory that the government, representing the people, does not have the right (even if it chooses not to exercise that right in every case) to prescribe who can use the spectrum and with what technological parameters.

Technology has brought us to the brink of a new chapter in television broadcasting. It now appears to be technically feasible to greatly increase the amount of television service -- i.e., the number of different programs of a given technical quality available to each viewer -- per unit allocated bandwidth. (I have dubbed this ratio "spectrum efficiency.") This new service is to be introduced in stages, which will culminate in turning off NTSC 10 years after digital broadcasting begins. The Commission has repeatedly called for the new system to be capable of nondisruptive improvement over time.

To protect the public interest during this momentous change, the Commission should ensure that receivers purchased by viewers for the initial broadcasts will remain usable as the system evolves. In addition, there is little doubt that the public will expect less expensive receivers to be available for less demanding applications, such as the small set often found in the kitchen. Likewise, it would be highly desirable to be able to use existing NTSC receivers after NTSC broadcasting ceases (Indeed, this is likely to be a political necessity.) Unfortunately, the Grand Alliance standard does not particularly cater to these last two desiderata, but the engineers may be able to come to the rescue, particularly as the monetary rewards for solving these problems will be considerable.

The responsibility for the continued usability of the early receivers is entirely in the hands of the Commission. Historically, receiver regulation has never been popular, although the All-Channel Receiver Law, which made UHF broadcasting practical, has been very successful. If the Commission prefers to leave receiver characteristics entirely to the market, then it must regulate the broadcasting format in such a way that any receiver that works acceptably with the early broadcasts will continue to work as the system is upgraded This does not mean that every DTV receiver must be an HDTV receiver or use progressive scan, but it does mean that every receiver must be able to display a usable image when it receives a progressive transmission in either HDTV or SDTV. *This can only be done if all transmissions are required, from the outset of DTV broadcasting, to be in progressive format with full vertical resolution.* Of course, the standards for the transmitted signal must be sufficiently detailed so that the functioning of receivers capable of decoding the first transmissions will continue to be so capable as modifications are made in the encoder, such as improved motion estimation.

With respect to the preference of cinematographers for a 2:1 aspect ratio, this is much too wide for much material that is used today. Aspect ratios wider than 16:9 can be accommodated by the letterbox method. Although not much used in the US, it has been widely used in Europe for widescreen films transmitted in 4:3 PAL, where as much as 25% of the screen height may be left blank. Only 11% of the height of the screen is lost when 2:1 programs are transmitted in a 16:9 system.

The preference for 72 or 75 fps rather than 60 fps by computer interests is much harder to satisfy. Upconversion at the receiver is possible but expensive. It would have been easier if my early suggestion had been followed that 24 fps be used for all subject matter, relying on upconversion to produce 48 fps or 72 fps at the receiver. (We actually got suprisingly good results with only 12 fps using sophisticated motion-compensated interpolation.) The success of Imedia Corporation in using this format for getting very high compression ratios when multiplexing many NTSC programs into one channel is an indication of what might have been possible. However, at this point, I think it is too late to make such a fundamental change in the proposed standard. This is another case where computer interests would have been well advised to spend enough money to develop a system that would be good for everyone.

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One may well ask why, if these considerations seem obvious to the author, that so many persons and entities in the industry favor interlace. My view is that, just as war is too important to be left to the generals, television is too important to be left to TV industry executives. In TV, it is evidently possible for nearly everyone to be wrong at the same time. No better example can be given than the near-universal opinion in the industry, at the outset of the current Inquiry, that HDTV must be compatible with NTSC, and that it would require more than 6 MHz. Likewise, digital transmission was widely considered a pipe dream, and contrary opinions on all these points were ridiculed. A strenuous attempt was made to foist MUSE off on the American scene. (MUSE came in last in the ATTC competition.) It is this background that the Commission is urged to keep in mind when evaluating the arguments that are now being presented.

Conclusions

It is evident that all of the principal arguments made in favor of allowing the use of interlace in early DTV broadcasting, as discussed in the Introduction, are faulty.

1. Even in analog TV, interlace does not double the vertical resolution for a given bandwidth. Because of the interline flicker that increases with resolution, it is possible to raise the resolution at most by about 10%. Interlace artifacts are introduced, and picture quality goes down.

2. When coding is used, progressive scan does not require more channel capacity . Studies at Bell Laboratories, RAI, NHK, and in France indicate that the higher correlation found in progressive sequences permits a doubling of the compression ratio so that the same coded data rate is required for either. Of course, the use of progressive scan eliminates the artifacts of interlace.

3. Interlaced receivers, which are likely to be somewhat cheaper than progressive receivers, at least initially, can still be used with progressive transmissions, although the displayed quality will be lower. The cost of the P-to-I converter in the receivers is so small as to be of no consequence. The I-to-P converter needed at the encoder when progressive transmission is used with interlaced source material does cost something, but that cost is negligible compared with the cost of converting to digital transmission.

4. The Polaroid development shows that, contrary to the predictions of the interlace enthusiasts, it is indeed possible to make a progressive-scan HDTV camera with excellent performance, including high sensitivity.

5. The conversion of existing NTSC program material into progressive form for multiplex transmission involves negligible cost as compared with the other costs of digital transmission. Progressive transmission from film, which will be very important to HDTV, involves no extra costs at all.

We conclude that, if a camera as good as the Polaroid camera had been available at the time of the ATTC/ATEL tests, and if subject matter had been used that exhibited strong interlace artifacts, the progressive systems would have won the competition. We further conclude that there are now no valid reasons for using interlaced transmission in DTV.

The use of progressive transmission is not primarily for the benefit of the computer industry; it is equally essential for high-quality television reception and to allow nondisruptive improvement of the broadcasting system over time, a long-standing Commission objective. Permitting interlaced transmission, on the other hand, will create a reverse-compatibility problem that will inhibit the eventual migration to a progressive format that everyone involved advocates. Finally, there is no cost penalty to any TV stakeholder, including viewers, in the exclusive use of progressive transmission.

Should the Commission accept this recommendation, the market can be relied up to ensure that cheaper interlaced receivers will remain useable as the system is upgraded, without any receiver regulation, provided that full vertical resolution is mandated in DTV broadcasting.

Appendix

1. E.F.Brown, "Low-Resolution TV Subjective Comparison of Interlaced and Noninterlaced Pictures," Bell System Tech. J., 46, 1, 1967, pp 199-232.

2. E. Petajan, "A Video Compression Efficiency Analysis using Progressive and Interlaced Scanning," AT&T Bell Laboratories, presented at the NIST Conference, Georgetown University, 1994, and at NAB 1994.

3. S.Pigeon and P. Guillotel, "Advantages and Drawbacks of Interlaced and Progressive Scanning Formats," EU Report R2110/WP2/DS/R/004/b1 commenting on the Scanning Formats Recommendation for Project Race in Jan. 1994.

4. M. Muratori (RAI), M. Stroppiana (RAI), and Y. Nishida (NHK), "Progressive and Interlaced Formats: Comparison and Coding Efficiency." (Similar to a paper by the same authors presented at the 1993 IEICE Spring Conference.)

5. "Further Results on the Comparison of Coding Efficiency Between Progressive and Interlaced Formats," Doc. TG CMTT/2-SRG-0?8 submitted to the CCIR Study Group TG CMTT/2 Jan. 1993.

6. S.M.Spitzer et al, "Design and Implementation of a 3-CCD, State of the Art. 750-line HDTV Progressive Scan Broadcast Camera." NAB 1996

7. Letter from the author to Mr. Hundt on 8 June 1996 relative to the effect of the I/P format on compressibility when a number of standard-definition programs are multiplexed into one 6-MHz channel.

8. Letter from the author to Mr. Hundt on 9 May 1996 relative to the significance of the Polaroid progressive-scan camera.

frames per second. The picture information is processed in real-time in a digital format. A digital memory is employed with sufficient capacity to store one complete frame of video information encoded as 8 digit PCM — a total of 204.8 kilobits at a rate of 1.536 MHz per second. Means are provided to introduce into the memory whole new pictures or selected picture elements at any interval which is a multiple of the frame rate. The information inserted into the memory is decoded and displayed on a monitor at a rate of 60 pictures per second in order to avoid flicker.

A number of frame repeating and replenishment systems have been demonstrated in real time using this equipment, however the system is in no way limited to those applications which have been discussed.

XVII. ACKNOWLEDGMENTS

The successful construction of this equipment has been the result of the efforts of many people who have contributed in many ways, and it is impossible to properly extend thanks to all of them for their efforts.

All work on this project was done under the direction of W. T. Wintringham. Other members of Bell Laboratories who have worked directly on this project and their responsibilities are: R. L. Eilenberger—TV camera equipment, E. M. Cherry—circuit design, J. E. Berrang—testing and alignment of encoder, R. C. Brainard and E. S. Bednar—frame memory, and J. A. Murphy—display system.

Much of the mechanical design work was done by H. T. Webber. I also wish to thank J. O. Edson, F. D. Waldhauer, J. H. Davis, E. F. Kovanic, and R. L. Klenk who assisted me in the duplication of their exploratory model PCM encoder-decoder equipment. The able help of the mechanical and wiring branch shops is also greatly appreciated.

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Low-Resolution TV: Subjective Comparison of Interlaced and Noninterlaced Pictures

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(Manuscript received September 19, 1966)

A subjective comparison of line-interlaced television pictures and noninterlaced television pictures has shown that the line-interlacing of low-resolution television pictures provides a bandwidth saving of considerably less than 2:1 when the line structure of the picture is visible.

A line-interlaced television picture was subjectively compared with several noninterlaced television pictures in an effort to determine their subjective equivalency in terms of bandwidth. Several other variables—noise, spot-wobble, line-width to line-pitch ratio, different models, illumination and luminance—were also employed in the experiments. The televised pictures consisted of a head-and-shoulder view of a model pantomiming a two-way conversation.

The results indicate that the line-interlacing of low-resolution television pictures provides about a 37 percent saving in terms of bandwidth at a relatively low value of high-light luminance of 40 fL (140 cd/m²) and as little as a 6 percent savings at a high-light luminance of 100 fL (340 cd/m²). When the line-width to line-pitch ratio is set at its preferred value for all pictures, a significant difference is obtained when the high-light luminance is decreased from 60 fL (200 cd/m²) to 40 fL (140 cd/m²). The effects of Gaussian noise, spot-wobble, illumination, and different types of models did not alter the subjective equivalence of line-interlaced and noninterlaced television pictures significantly. The addition of noise to a spot-wobbled picture was found to be more detrimental to the quality of the noninterlaced pictures than to the line-interlaced picture.

I. INTRODUCTION

The lower limit of the picture repetition rate for television pictures is dictated by the critical-fusion frequency (CFF).[1,2] The CFF is approximately proportional to the logarithm of the luminance over a wide range. It is also approximately proportional to the logarithm of the size of the flickering area. The CFF is on the order of 60 pictures per second for present day television luminances and picture sizes.

The television engineers of the 1930's experimented with two-fold line interlaced pictures as a means of saving bandwidth. In two-fold line-interlaced pictures, alternate lines are scanned during successive vertical deflection cycles. Engstrom[3] found that the vertical deflection cycle should be greater than 50 Hz and should be a multiple of the power line frequency. In 1941 the National Television System Committee (NTSC)[4] adopted a vertical deflection frequency of 60 Hz for two-fold line-interlaced commercial broadcast systems. Two-fold line interlace has since been adopted by virtually all television systems, regardless of the application.

One-half of the lines in a line-interlaced picture are scanned during alternate half-cycles of the frame rate which is 30 Hz. The result is essentially two light pulses for each frame period, i.e., an apparent rate of 60 light pulses per second. Thus, large-area flicker is negligible if present at all.

When all of the lines except one of a line-interlaced television raster are masked that line appears stationary and nonflickering. When all of the lines except two of a line-interlaced television raster are masked the two lines appear to jump back and forth as if in motion. When the masking is removed the whole raster appears to shimmer. When a picture is reproduced on the raster the shimmering is confined to small isolated areas of roughly equal brightness. The shimmering effect in these areas is most pronounced at brightness boundaries. This phenomena of apparent-motion is due to the out of phase relationship between adjacent lines of the raster and appears to be affected by the same laws as flicker. These apparent-motion defects are called interline flicker by the television industry.

Engstrom[3] found that interline flicker was visible at the same distance at which the line structure becomes visible. His conclusion was that the observer must be seated at a distance equal to or greater than that distance at which the line structure becomes resolvable.

Line crawling is another subjective defect associated with line-interlaced pictures. This stroboscopic defect takes the form of an apparent crawling of the lines either up or down depending on which direction the eye tends to track. Line crawling is related to the perceptibility of interline flicker and becomes increasingly perceptible with increasing picture brightness and angle subtended by the eye of adjacent line centers.

A third defect inherent to line interlaced pictures is subjective line-

pairing. Subjective line-pairing produces the same subjective impression as physical line-pairing, i.e., when adjacent lines are physically superimposed on each other by the deflection circuitry. Subjective line-pairing occurs when either the televised image or the observer's visual center of attention moves in a direction other than parallel to the scanning lines. This defect also occurs when the observer blinks his eyes or effectively strobes the picture. Subjective line-pairing is most evident when the motion is parallel to the vertical scan direction and at a rate equal to the field rate.

The question arises, "Do the degrading effects associated with interline flicker nullify the advantage of being able to present twice as much information in each picture when the line sturcture is visible"? Accordingly three subjective experiments were conducted in an attempt to answer this question.

The experiments were conducted on low-resolution television pictures. In the first experiment, a 225-line interlaced picture was compared with four noninterlaced pictures ranging from a 225-line picture to a 135-line picture in steps with ratios of $\sqrt[4]{2}$. Additional variables at two values each—noise, illumination, spot-wobble, and picture material—were also introduced. Two types of observers, skilled and nonskilled, were used.

The second experiment was performed in order to determine the effects of a change in luminance on the subjective relationship between the interlaced picture and the noninterlaced pictures. Five noninterlaced pictures were compared with the 225-line interlaced picture starting with a 189-line picture and decreasing in steps with ratios of $\sqrt[8]{2}$ to a 135-line picture. The subjective relationship between the noninterlaced pictures was also investigated.

For the third experiment, the preferred line-width to line-pitch ratio was determined in a separate experiment. In this experiment, the line-width to line-pitch ratio was set at the preferred value for each picture. The 225-line interlaced picture was compared with 5 noninterlaced pictures starting at a 225-line picture and decreasing to a 147-line picture in steps with ratios of $\sqrt[8]{2}$. Two levels of luminance were introduced as a second variable.

The bandwidth in each of the above cases was adjusted such that the vertical to horizontal resolution ratio was approximately 1:1.[5] A-B testing techniques were used. Each A-B pair consisted of the interlaced picture and one of the noninterlaced pictures except for that portion of the second experiment where the noninterlaced pictures were compared against each other.

II. TEST APPARATUS

The basic operation and layout of the test apparatus is illustrated by block diagrams shown in Figs. 1 and 2.

Fig. 1 illustrates the basic functions of the counting and sync signal generating apparatus. The vertical counting and vertical sync generating apparatus was held constant for all picture rates. The vertical sweep rate was 60 Hz. Two sets of horizontal counters were used. The counters were programmed to produce the desired line rate by opening and closing appropriate leads with remote controlled relays. The proportion of the horizontal blanking period to the line period was kept constant for all rates at $\frac{1}{6}$ of the line period. The vertical blanking period was held constant at $\frac{1}{16}$ of the field period.

The ratio of the vertical divisor to horizontal divisor was an integer for the noninterlaced pictures. The ratio of the two divisors was an integer plus one-half for the interlaced picture.

Fig. 2 illustrates the basic operation of the rest of the test apparatus.

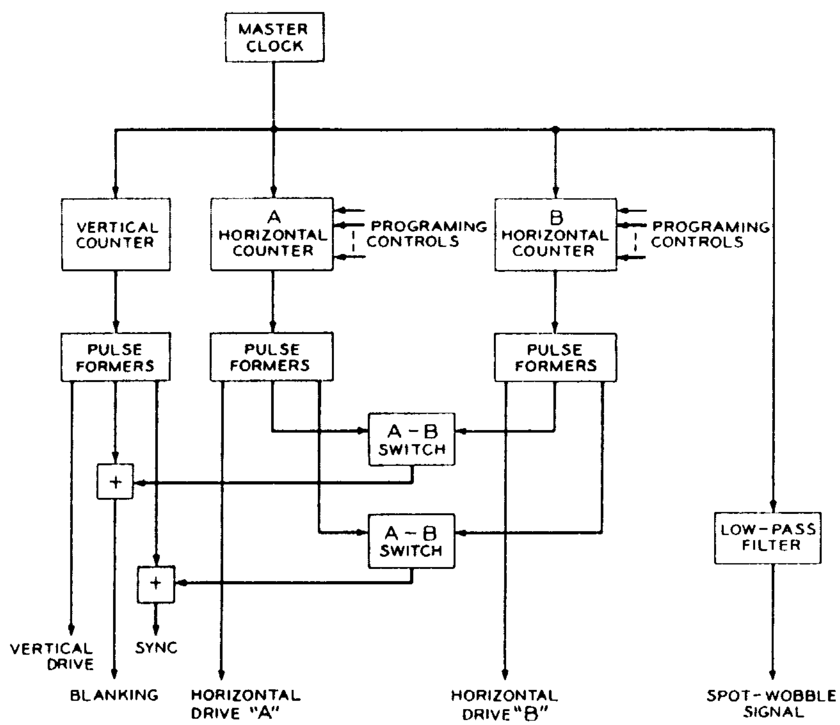


Fig. 1 — Simplified block diagram of sync generator and pulse forming apparatus.

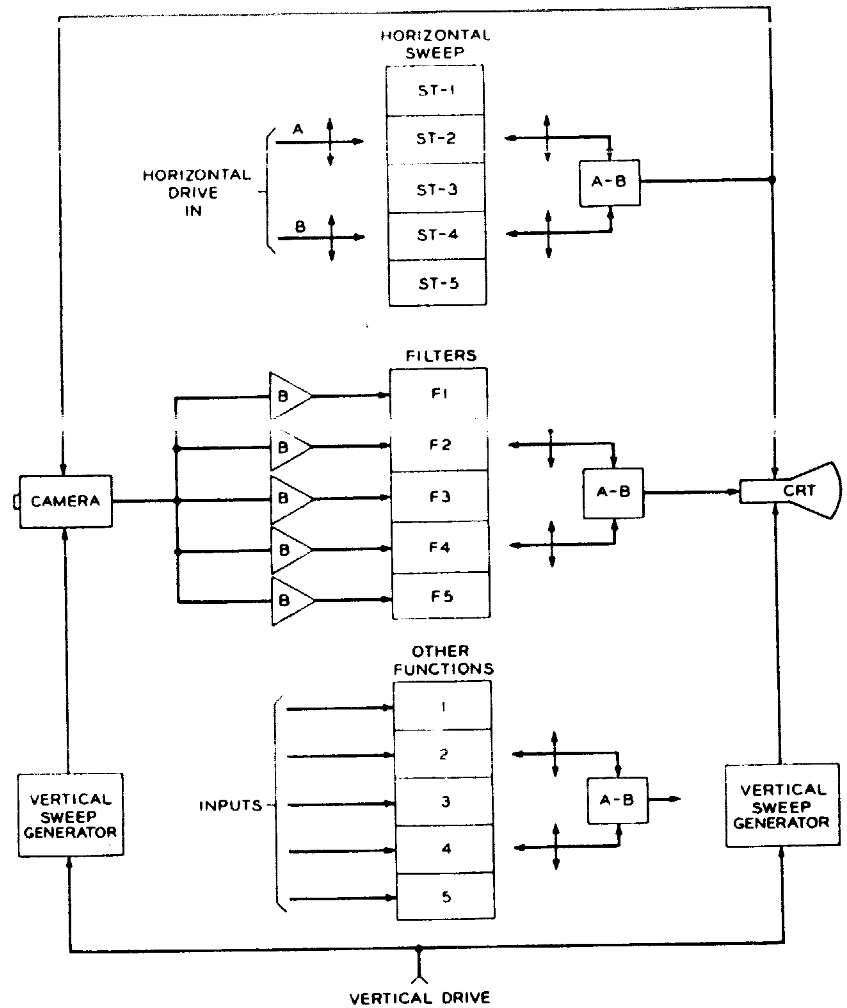
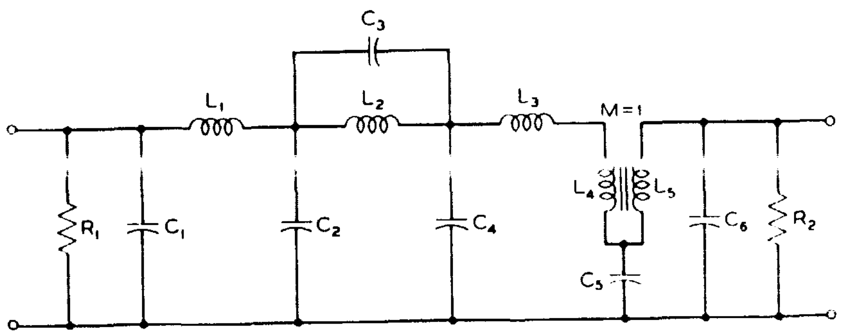


Fig. 2 — Simplified block diagram of test apparatus.

An RCA TK-21 camera chain was the core of the camera end of the test apparatus. Six horizontal sawtooth generators were used to accommodate six different sweep rates. These were carefully designed driven circuits which provided a sweep linearity on the order of ± 1 percent of full scale deflection. Remote-controlled relays were used to preselect the two sawtooth signal generators. The two sawtooth signals for driving both camera and monitor sweeps were then applied to an A-B switch which selected the desired one of the pair.

Great care was taken in the design and construction of the sweep and associated circuits to insure that line spacing on the pick-up tube and display tube was correct in all cases.

Six low-pass filters were provided for processing the picture signals of the six different sweep rates. The filters were isolated from each other with buffer amplifiers. The appropriate filter for each sweep rate was selected by remote-controlled relays. Each filter had an ad-



(a)

$fd = f_{co}/1.57$ | $R_2 = 0.3257\,R_1$
$L' = \dfrac{R_1}{0.952\,fd}$ | $C' = \dfrac{1}{0.952\,R_1 fd}$
$L_1 = 0.1195\,L'$ | $C_1 = 0.04709\,C'$
$L_2 = 0.1600\,L'$ | $C_2 = 0.1581\,C'$
$L_3 = 0.1303\,L'$ | $C_3 = 0.03189\,C'$
$L_4 = 0.0357\,L'$ | $C_4 = 0.4856\,C'$
$L_5 = 0.05568\,L'$ | $C_5 = 1.438\,C'$
 | $C_6 = 0.1292\,C'$

(b)

Fig. 3 — Low-pass filter: (a) circuit diagram, (b) design data.

justable attenuator which permitted balancing for the difference in insertion losses.

Each filter had a near Gaussian roll-off, had linear phase, and exhibited a preshoot and overshoot in its step response.* The preshoot and overshoot were each 12 percent of the step-signal amplitude. The cutoff frequency for the filters was arbitrarily selected as the −20-dB point on their response curve. Fig. 3 shows the circuit configuration and design data for the filter.† Fig. 4 shows the typical amplitude

* An earlier experiment (unpublished) indicated subjectively that this type of filter gave the preferred picture rendition.

† Designed by G. Szentermai of Bell Telephone Laboratories, Incorporated.

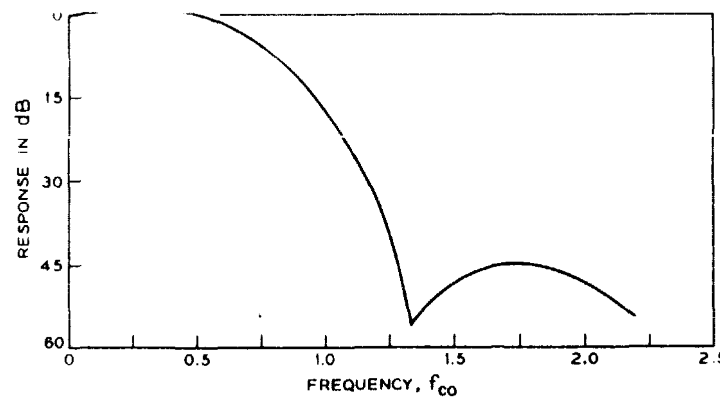


Fig. 4 — Relative amplitude versus frequency response characteristics of low pass filter.

versus frequency characteristics of these filters and Fig. 5 the typical step response. After adjustment of the effective vertical resolution by applying a Kell factor of 0.7 and allowing for the difference between vertical and horizontal blanking periods, the cutoff frequency (−20 dB) of the low-pass filters was selected to provide approximately equal horizontal and vertical resolution.[5]

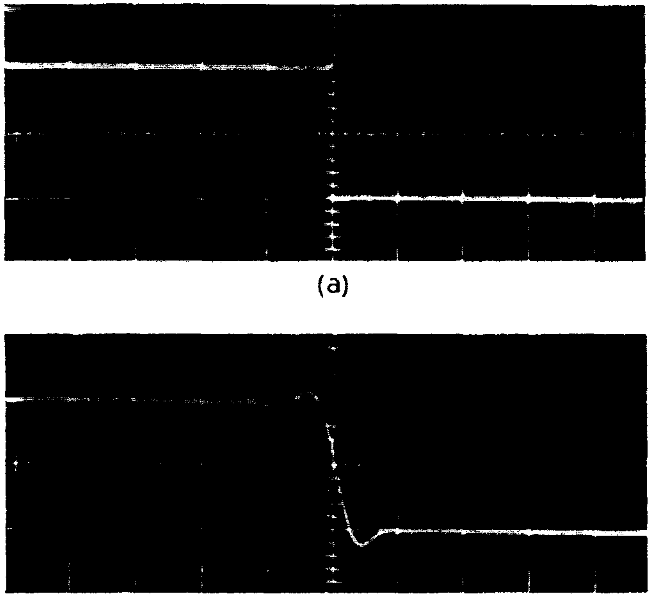
Three other functions were selected and switched in much the same manner. These were spot-wobble, line width to line pitch ratio and camera raster centering. Each of these functions had its individual balancing controls.

The spot-wobble signal was a 7.1442-MHz sine wave locked to the master clock. The spot-wobble signal was applied to the picture tube through an auxiliary yoke. The line broadening by the spot-wobble signal was subjectively optimized for and by the experimenter for each test picture. In general, the line broadening was adjusted such that a minute gap appeared between adjacent lines.

The line-width to line-pitch ratio without line broadening was about 0.33 for the 225-line interlaced picture. The line-width was measured at the half-luminance level of the line profile. The line-width to line-pitch ratio for the other pictures may be determined by

$$LW/LP = 0.33\left(\frac{L_p}{225}\right), \tag{1}$$

where L_p is the number of lines in the picture. Fig. 6 shows line profiles of the scanning lines perpendicular to the direction of scan for an interlaced and noninterlaced picture.



(a)

(b)

Fig. 5 — Step response of low-pass filter: (a) input to filter, (b) output of filter illustrating 12 percent preshoot and overshoot about step.

Fig. 7 shows line profiles of spot-wobbled scanning lines perpendicular to the direction of scan for an interlaced and noninterlaced picture. (The asymmetry of the spot profile is due to a slight misalignment in the position of the auxiliary yoke.) At the juncture of adjacent lines the luminance level of each line was about 25 percent of its maximum luminance. Since the period between adjacent lines for the interlaced picture is 1/60 second the observer will see the sum of the contributions of each line at their juncture.[2] Therefore, in the spot-wobbled line-interlaced pictures the brightness at the juncture of adjacent lines was about

$$B_i = 1/4(B_1 + B_2), \tag{2}$$

where B_i = brightness at the junction of adjacent lines, B_1 = maximum brightness of line one, and B_2 is the maximum brightness of line two.

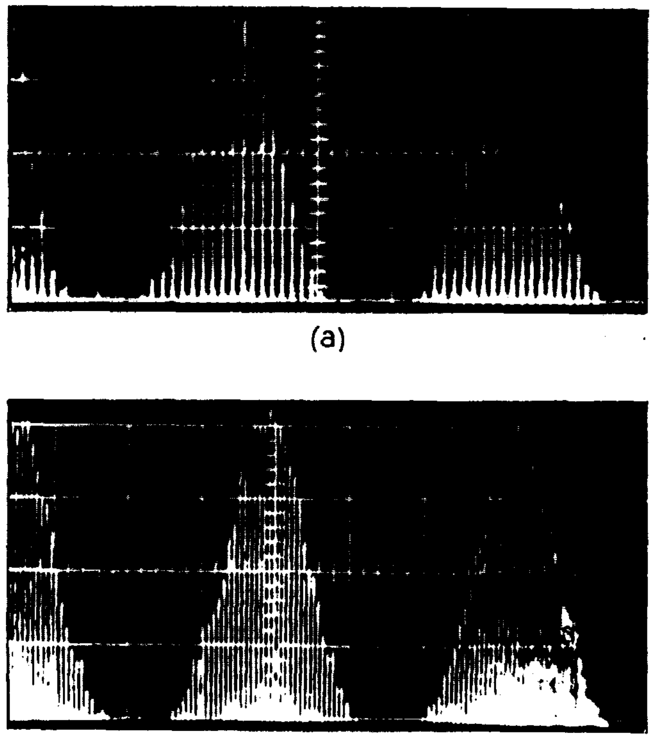
The Talbot-Plateau Law[2] says that an observer watching flashing lights above the CFF will sense an apparently constant mean value of the luminance of the lights over the period of the flashes. Equation (2) is a special case of the Talbot-Plateau Law. The law must be expressed

in its complete form to cover the spot wobbled noninterlaced pictures. The Talbot-Plateau Law is

$$Lm = \frac{1}{T}\int_0^t L\,dt, \tag{3}$$

where Lm is the mean value of the real luminance taken over one period or over any time t comprising an integral number of periods.

With spot-wobbled noninterlaced pictures the period between successive excitations of the phosphor at the juncture of adjacent lines is one line period. Since the phosphor has a finite decay time, it will still be luminescing at the juncture of adjacent lines when excited the second time. Thus, the luminance generated by the second excitation will add to that remaining from the first excitation. The second excita-



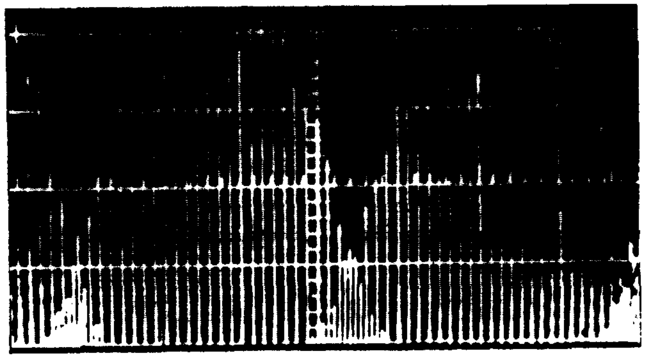
(a)

(b)

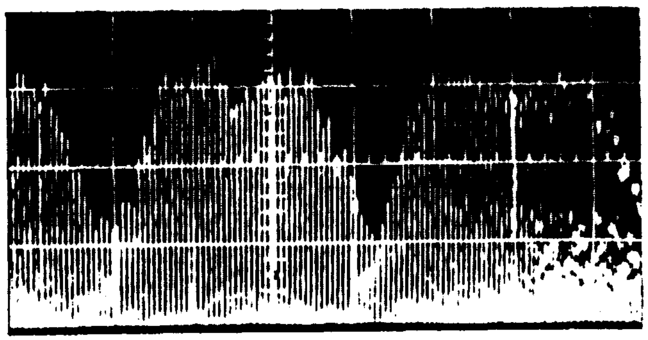
Fig. 6 — Experiment I—profiles of picture-tube scanning lines. (a) 225-line interlaced picture with line width to line-pitch ratio of 0.33, (b) 189-line noninterlaced picture with line-width to line-pitch ratio of 0.28.

tion one line period later at the juncture of adjacent lines, according to the Talbot-Plateau Law, increased the mean luminance at the juncture by about 25 percent.

Asymmetrical spot defocussing was obtained by placing two electromagnets about the neck of the picture tube such that they defocussed the scanning spot perpendicular to the direction of line scan only. Another experiment[6] has shown that the preferred line-width to line-pitch ratio for line-interlaced pictures is about 1.7 and for noninterlaced pictures is about 1.2. Fig. 8 shows the effect of defocussing the scanning spot perpendicular to the direction of scan for a line-interlaced picture. When the line-width to line-pitch ratio is 1.7 the luminance contributed by a line at the juncture of adjacent lines is about 82 percent of the luminance at the center of that line. For a noninterlaced picture with a line-width to line-pitch ratio of 1.2 the luminance contributed by a line at the juncture of adjacent lines is about 60 percent of the luminance at the center of that line. Equations (2) and (3) are also applicable in these cases.



(a)



(b)

Fig. 7 — Experiment I—profiles of picture tube scanning lines with spot-wobble. (a) 225-line interlaced picture, (b) 189-line noninterlaced picture.

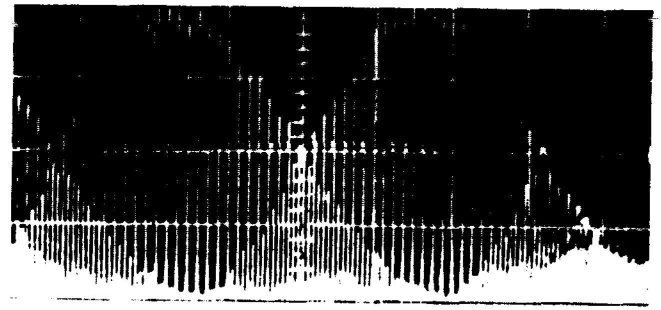


Fig. 8 — Experiment III—profiles of picture tube scanning lines with line-width to line-pitch ratio of 0.9 where the overlap at the juncture of adjacent lines is approximately 50 percent.

Switching between the A-B pairs was instantaneous in so far as the observer was concerned. Switching between A-B pairs was under the control of the observer. The switching action started with the leading edge of the vertical drive pulse and was completed during the vertical blanking interval so that visible transients were minimized.

The test appartus was checked out twice each day to insure that all apparatus was operating correctly and aligned properly.

The test room, Fig. 9 was a specially constructed room which was remote from the experimenter's station. Audio communication between experimenter and observer was over an intercom. The intercom was a push-to-talk type which permitted noise (switching, etc.) isolation between the test room and experimenter's station.

The observer was seated in a comfortable chair at a distance of about 40 inches from the screen of the monitor. The picture size was 5 inches by 5 inches for each case.

III. TEST PROCEDURE AND INSTRUCTIONS

A-B testing techniques were employed in which one of the pictures was always the interlaced picture. The two pictures were presented in sequential order under the control of the observer.

Once an A-B pair was selected by the experimenter, control of the A-B switch was turned over to the observer. The observer switched

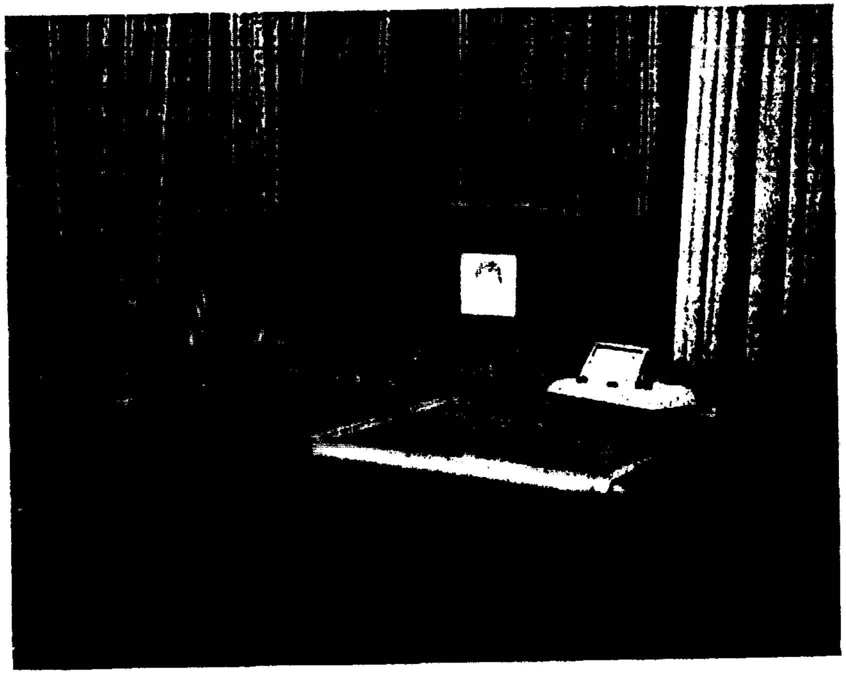


Fig. 9 — Test room.

between the two pictures of the A-B pair at will and for as long as he wished until he reached a decision. After each observer's decision, the experimenter presented to the observer a uniform gray raster set near the average luminance level of the picture during which time the experimenter selected the next A-B pair. Set-up switching time was about 5 seconds.

The oral instructions to each observer were:

"You will be shown 32 sets of pictures to compare. Each set will consist of 2 pictures. The pictures between sets and within sets will be different.

"The A picture will appear when you depress this A button and the B picture will appear when you depress this B button. You may switch back and forth as often as you wish and for as long as you wish.

"Once you have decided which picture you like best, please announce your preference over the intercom as A or B."

Each of the 25 observers made a forced choice decision for one of the two pictures in each of the 32 pairs. The total observation time for observers varied from 15 minutes to 30 minutes.

Question and answer sessions were held after each test session. All of the observers detected the subjective picture defects due to interlacing. Their description of these effects was in terms of noise. It appears that their preferences was an expression of their reaction to the annoying effects of "noise" in the line-interlaced picture.

IV. EXPERIMENTAL DESIGN—EXPERIMENT I

The objective was to determine subjectively how much saving in bandwidth a line-interlaced picture provides with respect to a noninterlaced picture. The most straightforward experimental design was the Method of Constant Stimuli[7] in which the constant (or reference) picture was a line-interlaced picture which was compared with several noninterlaced pictures with different numbers of lines and bandwidths. The noninterlaced pictures provided a physical scale on which a point of subjective quality (PSE) could be estimated for the interlaced picture.

A 225-line picture was selected as the reference interlaced picture. This picture (as well as the noninterlaced pictures) was displayed on a 5 inch $\times$ 5 inch raster. At this picture height and a viewing distance of 40 inches, the 225-line interlaced picture had an angular subtense between adjacent lines of 2.2 minutes of arc (see Table I). Four noninterlaced pictures were used starting with a 225-line picture and decreasing in steps with ratios of $\sqrt[4]{2}$ to a 135-line picture, Fig. 10.

Two levels of noise were introduced as test variables. The first or zero level was that introduced by the test apparatus. Most of this noise, just above threshold, was contributed by the vidicon camera. The second or added noise had a Gaussian distribution. The peak-to-

TABLE I — SOME PARAMETERS OF EXPERIMENTAL APPARATUS (EXPERIMENT I)

Number of lines	Line-interlace	Horizontal sweep rate (Hz)	Bandwidth (MHz)	Picture elements/frame	Visible picture elements/frame	Visible picture elements/line	Angular subtense between two lines at 40″
225	Yes	6750	0.575	38,333	28,366	142	2.2′
225	No	13,500	1.154	38,466	28,366	142	2.2′
189	No	11,340	0.812	27,066	20,029	119	2.5′
162	No	9720	0.575	19,166	14,183	102	2.9′
135	No	8100	0.413	13,766	10,186	85	3.4′

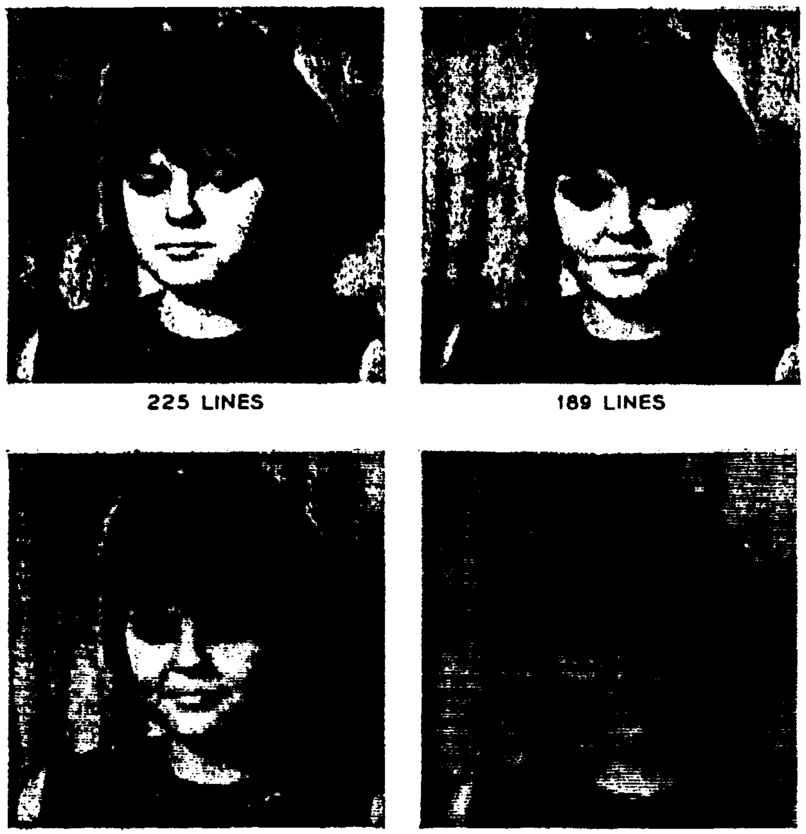
peak picture signal to added rms noise level was set at 30 dB for the interlaced picture with a bandwidth of 575 kHz. For the noninterlaced pictures, the peak-to-peak picture signal to rms noise was

$$S/N = 30 \text{ dB} - 10 \log \frac{Bw}{575\text{kHz}} \tag{4}$$

where Bw is the bandwidth of the noninterlaced picture. (See Table II).

Two levels of illumination were used 25 fc (275 lm/m^2) and 50 fc (550 lm/m^2). Although the luminance was not adjusted it varied with illumination as follows:

Illumination	High-light luminance	Low-light luminance	Contrast ratio
25 fc (275 lm/m^2)	100 fL (340 cd/m^2)	9 fL (30 cd/m^2)	11 : 1
50 fc (550 lm/m^2)	105 fL (360 cd/m^2)	20 fL (70 cd/m^2)	5 : 1



225 LINES

189 LINES

162 LINES

135 LINES

Fig. 10 — Photographs of noninterlaced pictures.

TABLE II — EXPERIMENT I: FREQUENCY OF PREFERENCE FOR NONINTERLACED PICTURES OVER 225-LINE INTERLACED PICTURE FOR THE VARIOUS CONDITIONS OF THE TEST

	Additional variables	$\overline{N}$-$\overline{SW}$-$\overline{I}$	N-$\overline{SW}$-$\overline{I}$	$\overline{N}$-SW-$\overline{I}$	N-SW-$\overline{I}$	$\overline{N}$-$\overline{SW}$-I	N-. $\overline{W}$-I	$\overline{N}$-SW-I	N-SW-I	Summed over all variables
	Number of test sets	25	25	25	25	25	5	25	25	200
Number of lines (non-interlaced)	135	1	1	3	1	1	1	3	2	13
	162	10	14	13	10	12	1	17	15	102
	189	23	20	25	21	23	2	22	18	174
	225	25	25	25	25	25	5	25	24	199

$\overline{N}$ = System noise

N = Signal/noise— 135 lines noninterlaced = 31.4 dB; 162 lines noninterlaced = 30.0 dB; 189 lines noninterlaced = 28.6 dB; 225 lines noninterlaced = 27.0 dB; 225 lines interlaced = 30.0 dB

$\overline{SW}$ = no spot-wobble

SW = spot-wobble

$\overline{I}$ = illumination of 25 fc (275 lm/m^2)

I = illumination of 50 fc (550 lm/m^2)

The change in luminance is due to the change in the amount of reflected light from the safety glass with a change in the illumination. Subsequent measurements of the low-light luminance indicated the 20 fL (70 cd/m^2) measurement is probably in error on the high side.

Spot-wobble was introduced at the picture tube as another variable. Fig. 11 illustrates the effect of spot-wobble on the received picture.

Two types of observers, skilled and nonskilled, were used in the test. Skilled observers were considered those who work in the television engineering field. Nonskilled observers were considered those whose only prior experience was home viewing of their commercial receivers. Thirteen skilled and twelve nonskilled observers were used.

Two young women were used as models. One was blonde with fair

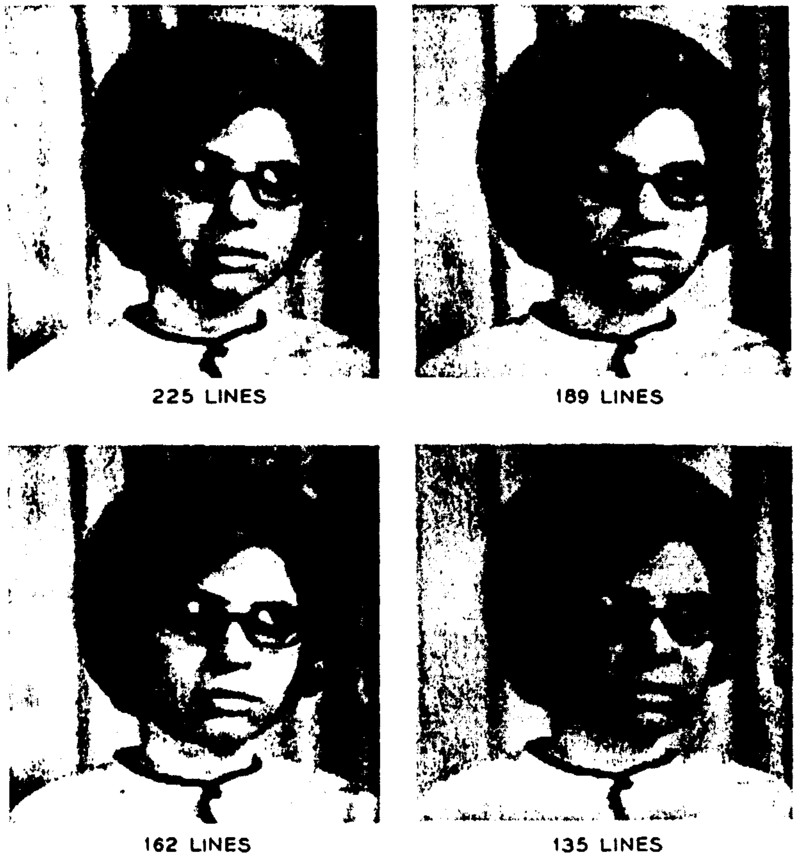


Fig. 11 — Photographs of noninterlaced pictures with spot-wobble.

complexion who wore black horn-rimmed glasses and the other was brunette with dark complexion. During the test, the models pantomimed what might be considered a face-to-face conversation. Subjective line-pairing, not investigated in this experiment, was minimized by instructing the models not to make rapid movements or movements which were perpendicular to the scanning lines. The observers were partially immobilized in the same sense by requiring them to operate the A-B switch whose position was fixed. The observers were not cautioned as to their movements otherwise. Fig. 10 shows the brunette model for the four noninterlaced pictures. Fig. 11 shows the blonde model for the four noninterlaced pictures with spot-wobble. The 225-line interlaced picture is not shown since photographically it would appear the same as the 225-line noninterlaced picture.

The order in which the interlaced picture and the noninterlaced pictures appeared in the A-B positions on the buttons was determined by a random number table.

Each observer saw 32 A-B pairs where each pair consisted of the interlaced picture and one of the 4 noninterlaced pictures. When used, the additional variables noise, spot-wobble, illumination and combinations thereof were added to both pictures of the A-B pair. The order of presentation of the noise and spot-wobble variables was also randomized with random number tables. The level of illumination was set at one value during the first half of each session and set at the other value during the second half of each session. Successive observers started their test session with alternate levels of illumination.

Seven of the skilled observers and six of the nonskilled observers saw the blonde model and six of each saw the brunette model.

V. EXPERIMENT I—RESULTS AND CONCLUSIONS

Table II lists the ferquency of preference for the noninterlaced pictures over the 225-line interlaced picture for the variables employed in this experiment.

In the tables and the text, the response data is generally related in terms of the number of noninterlaced lines, whereas the objective is to determine the bandwidth savings of interlaced pictures over noninterlaced pictures. However, on the data graphs the ordinate of the curves is expressed in terms of the number of noninterlaced lines, *Ln*, and the bandwidth improvement ratio with line-interlace, *Bi*. The reference for the bandwidth improvement factor is a hypothetical 159-line noninterlaced picture with a bandwidth of 575 KHz. The number of noninterlaced lines, *Ln*, may be converted to bandwidth improvement ratio with line-interlace, Bi, by

$$Bi = \frac{Ln^2}{159^2}. \tag{5}$$

The frequency of preference data listed in Table II was converted to percentiles. On the hypothesis that the percentile score was cumulative normal a maximum likelihood probit[8] regression line was computed for each set of data. A χ^2 test was performed on each of the regression lines. Since none of the χ^2 values exceeded the value of the number of degrees of freedom less one, there appears to be no conflict with the hypothesis that the data is cumulative normal.

The probit regression line and the original data points are plotted on each of the graphs.* In addition, the following information is listed in tabular form on each graph, (*i*) the point of subjective equality (PSE) in terms of number of noninterlaced lines, (*ii*) the standard deviation of the distribution, σ, and (*iii*) the standard error of the PSE, SEP.†

The method of the standard error of the difference[9] was used in determining the significance of a difference between two PSE's in the following manner. The standard error of the difference between two independent random variables, is equal to the square root of the sum of their variances. Therefore, assuming independence,

$$\sigma_{PSE} = \sqrt{SEP_1^2 + SEP_2^2}\,, \tag{6}$$

where σ_{PSE} is the standard error of the difference between PSE's and SEP^2 is the variance of the PSE's. The χ^2 test indicated no conflict with the hypothesis that the PSE's are from a normal distribution, thus the distribution of the difference between the distributions of the curves from which the PSE's will be drawn is normal.

The test for significance was made in terms of T which is the difference between the PSE's expressed in terms of σ_{PSE} as

$$T = \frac{|\,PSE_1 - PSE_2\,|}{\sigma_{PSE}}. \tag{7}$$

Adopting a null hypothesis that the two PSE's belong to the same parent distribution, we may set our confidence limits at a probability level of 0.05. Thus, a value of the normal deviate T of 1.96 or greater will indicate a significant difference between two PSE's.

* When data points are missing from the data plots they represent a zero or 100 percentile score, which is not visible on the graphs.

† Each of these values are weighted best estimates. Finney, Ref. 8, gives an excellent description of the statistical techniques used in arriving at these values.

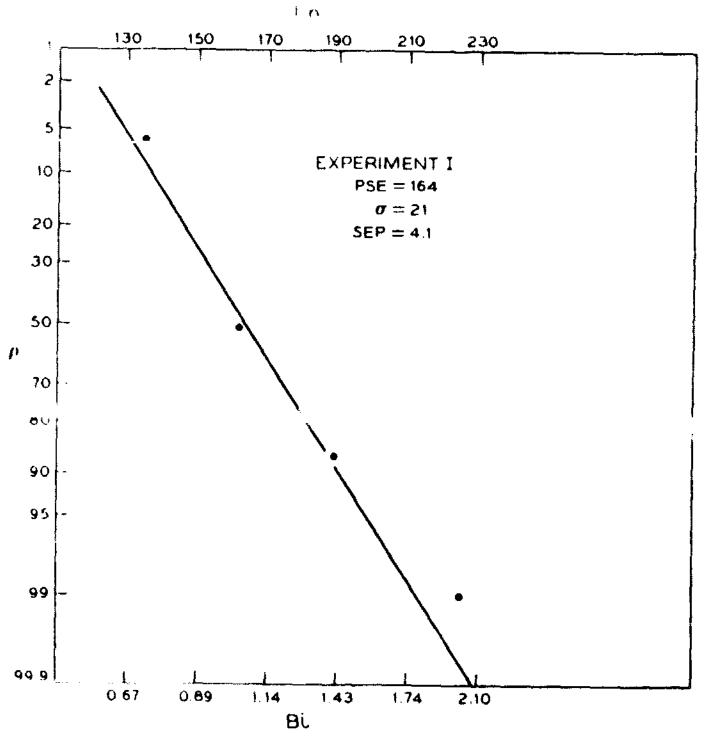


Fig. 12 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture summed over all additional variables.

The preference percentile scores for the four noninterlaced pictures over the interlaced picture summed over all additional variables is plotted in Fig. 12. The PSE of the 225-line interlaced picture with respect to the noninterlaced picture is approximately a 164-line picture (Bi = 1.06) with a standard deviation of about 21 lines and a SEP of 4.1 lines.

Significant first-order interactions between the additional variables was found only between the spot-wobble and added noise variables. This interaction is illustrated in Fig. 13 where curves of the preference percentile scores versus number of noninterlaced lines for spot-wobble without added noise summed over the other variables and spot-wobble with added noise summed over the other variables is plotted. The PSE for spot-wobble without added noise is a 157-line picture (Bi = 0.98) whereas for spot-wobble with added noise the PSE is a 167-line picture

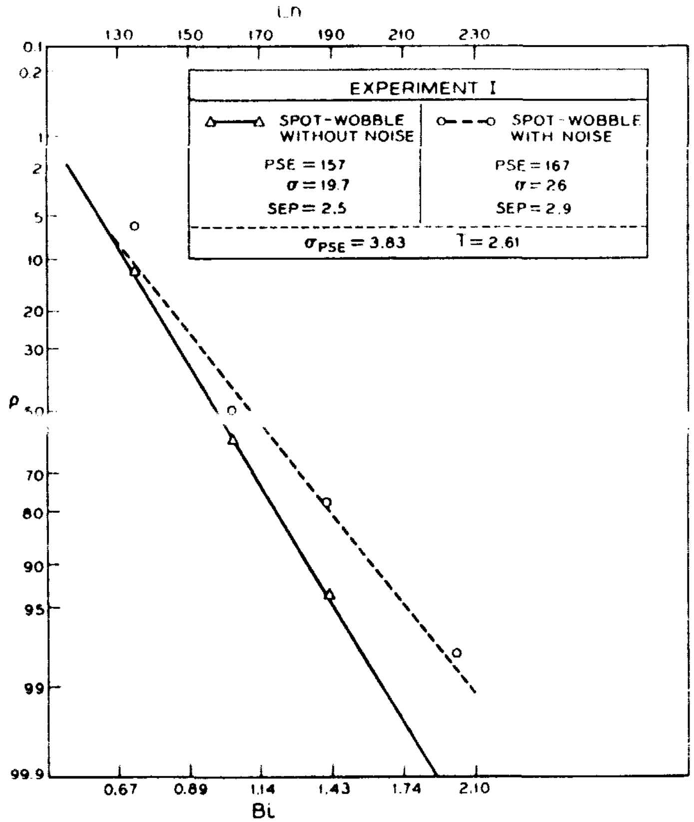


Fig. 13 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture with spot-wobbled picture-tube scanning beam: (a) without added noise, and (b) with added noise. (Summed over all additional variables.)

(Bi = 1.10). A T-score of 2.61 indicates there is a significant interaction between noise and spot-wobble.

The first-order interaction between spot-wobble and noise precludes a check on the main effects of these two variables summed over the other. Therefore, the interacting variable must be eliminated in the analysis of their main effects. Fig. 14 shows the preference percentile score of the noninterlaced pictures over the interlaced picture for three cases, (i) summed over all additional variables except spot-wobble and added noise, (ii) spot-wobbled scanning beam summed over all additional variables except added noise (also shown in Fig. 13), and (iii) added noise summed over all additional variables except spot-

wobble. The results are itemized below:

	Case 1	Case 2	Case 3
PSE	165	157	166
Bi	1.08	0.98	1.09
σ	17	20	20
SEP	5.1	2.5	5.6

A T-score of 1.4 for case 1 versus case 2 indicates that spot-wobbling of the scanning beam does not significantly effect the results. Also the

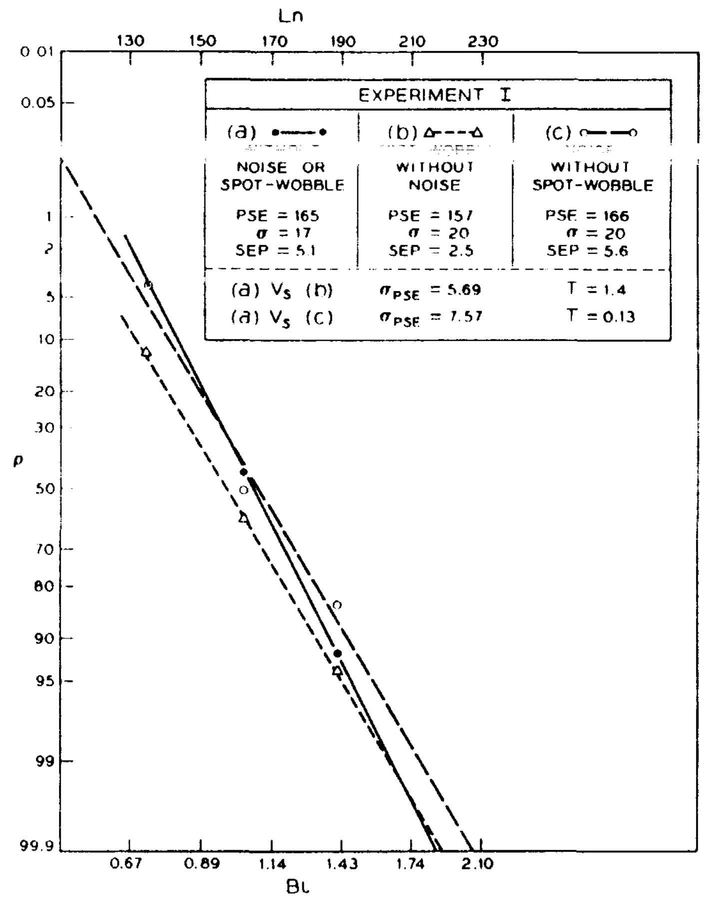


Fig. 14 — Experiment I—the preference for noninterlaced pictures over a 225-line interlaced picture: (a) summed over all additional variables except added noise and spot-wobble, (b) spot-wobbled picture-tube scanning beam, summed over all additional variables except noise, and (c) added noise summed over all additional variables except spot-wobble.